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MEMORANDUM REPORT ARBRL-MR-03355

AN EXPLANATION OF SPIN-UP INSTABILITIES FOR A 155MM BINARY PROJECTILE

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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In 1971 during the development testing of the 155mm XM687 binary projectile, liquid-induced flight instabilities were observed. Tests were conducted that indicated unstable behavior for fill ratios of 80-100%. However, stable flights occurred for a fill ratio of 65%. A solid, cylindrical spacer was fitted to the interior of the aft end of the rear payload canister, thus shortening the overall interior length of the payload compartment. This simple

(continued)

modification yielded stable flights and was incorporated into the standard projectile. This report presents yawsonde data and analytical models that explain the stabilizing effect of the spacer which was eventually employed in the M687 projectile.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

A cutaway view of the 155mm XM687 binary projectile is shown in Figure 1. During the early 1970's, flight instabilities of the XM687 were reported and investigated at Dugway Proving Ground (DPG, then called the Deseret Test Center), Utah.[1,2,3] Mark and Mermagen conducted yawsonde tests to investigate flight stability,[4] and Mark analyzed yawsonde data from several M687 tests.[5] However, a clear explanation as to the mechanism of the flight instability has not been presented. Figure 1 shows a spacer within the rear canister. The original projectile design did not have this spacer and was unstable. This report will explain the flight behavior of the M687, with and without the spacer, through the use of analytical models (spin-up and steady state) and yawsonde data.

II. BACKGROUND

Figure 2 (extracted from Reference 5) gives a summary of impact data from the early DPG tests. If a normal range was not achieved, then that round was scored as a failure. The probability of failure is plotted versus fill ratio. During the initial development of the M687, the only available theory addressing the flight stability of a liquid-filled shell was the Stewartson-Wedemeyer model.[6,7] This linearized, steady state model can only be applied when the liquid has a rigid body velocity distribution. Yawsonde data in Figures 3 and 4 (Figure 3 is previously unpublished data by Mark and Mermagen, while the data in Figure 4 were taken from Reference 4) indicate yaw growth as early as 2-5 seconds after launch. Wedemeyer presented a model for spin-up from rest of a completely filled cylinder in 1965; however, only inviscid solutions

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1. *C. C. Sterns and K. Jones, "Phase 1 of Malfunction Investigation Test for Projectile, 155mm, GB2, XM687," Deseret Test Center Data Report (DTCDR) Phase 1-72-305, Deseret Test Center, Fort Douglas, Utah, October 1971.*

2. *C. C. Sterns and K. Jones, "Phase 2 of Malfunction Investigation for Projectile, 155 mm, BG2, XM687," Deseret Test Center Data Report (DTCDR) 72-305, Deseret Test Center, Fort Douglas, Utah, 3 April 1972.*

3. *C. C. Sterns and K. Jones, "Phase 3 of Malfunction Investigation Test Projectile, 155mm, XM687," Deseret Test Center Data Report (DTCDR) 72-305, Deseret Test Center, Fort Douglas, Utah, 3 April 1972.*

4. *A. Mark and W. H. Mermagen, "Measurement of Spin Decay and Instability of Liquid-Filled Projectiles via Telemetry," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report No. 2333, October 1973. (AD 771919)*

5. *A. Mark, "Measurements of Angular Momentum Transfer in Liquid-Filled Projectiles," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Technical Report ARBRL-TR-2029, November 1977. (AD A051056)*

6. *K. Stewartson, "On the Instability of a Spinning Top Containing Liquid," Journal of Fluid Mechanics, Vol. 5, Part 4, September 1959, pp. 577-592.*

7. *E. G. Wedemeyer, "Viscous Corrections to Stewartson's Stability Criterion," Ballistic Research Laboratories Report 1325, June 1966. (AD 489687)*

were presented.[8] Even from Wedemeyer's initial theory, a characteristic time to spin-up could be computed for either a laminar or a turbulent boundary layer. Recently, Sedney and Gerber have included the effects of viscous diffusion in the Wedemeyer model and have summarized the characteristic spin-up times.[9] Concepts from Reference 9 will be summarized here. The Reynolds number (Re) is defined using the canister radius (a), the projectile spin rate ($\dot{\phi}$), and the kinematic viscosity of the liquid (ν),

$$Re = a^2\dot{\phi}/\nu \tag{1}$$

The characteristic times for spin-up (the e-folding time) are:

$$t_s = (2c/a)\ Re^{1/2}/\dot{\phi} \qquad \text{for } Re < 10^5 \tag{2}$$

$$t_{st} = (28c/a)\ Re^{1/5}/\dot{\phi} \qquad \text{for } Re > 10^5 \tag{3}$$

The half height of the payload cylinder is c; thus, the aspect ratio is c/a. The aspect ratio of the XM687 (without the spacer) was 4.90. Typical spin rates and Reynolds numbers for the DPG tests were 100 Hz and 10^6. From Eq. (3), the characteristic turbulent spin-up time was approximately 11 seconds, which is a substantial portion of the total flight time. The yawing motion shown in Figures 3 and 4 must have been produced by a spin-up, not a Stewartson-Wedemeyer, instability. Figure 5 (also unpublished data by Mark and Mermagen) shows yawsonde data for an XM687 with the spacer in place (c/a = 4.39). No unstable behavior is evidenced.

It is important to note that during the early 1970's, the M483 family of shell (the M687 is a member of that family) utilized a half caliber boattail.[10] This boattail was reduced in length to a quarter caliber to improve projectile stability for transonic launch conditions. The flight instabilities documented in Reference 3 all occurred for transonic launch conditions (Charge 4). The cross coupling between a liquid-induced moment and poor aeroballistic performance is not clearly understood; however, the data within

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8. *E. H. Wedemeyer, "The Unsteady Flow Within a Spinning Cylinder," Ballistic Research Laboratories Report 1225, October 1965. (AD 431846)*

9. *Raymond Sedney and Nathan Gerber, "Viscous Effects in the Wedemeyer Model of Spin-Up from Rest," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Technical Report ARBRL-TR-02493, June 1983. (AD A129506)*

10. *W. P. D'Amico, V. Oskay, W. Clay, "Flight Tests of the 155mm XM687 Binary Projectile and Associated Design Modifications Prior to the Nicolet Winter Test 1974-1975," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report BRL-MR-2748, May 1977. (AD B019969L)*

Figure 3 show yaw growth at an amplitude of 2.5 degrees, and normally much larger angles of attack were required to produce an M483-type aeroballistic instability. Given the quarter-caliber boattail and improved aeroballistic damping of the M483 family, it is not certain that unstable, liquid-induced behavior would be observed for $c/a = 4.90$.

Several of the DPG test rounds had a fill ratio of 80% (water was used), since the actual binary agent system has an initial fill ratio of 80%. Subsequent to launch and mixing, the binary system will produce fill ratios that may approach 100%. As such, much of the data and rationale discussed in this report will be collapsed to the 100% case. The spin-up analyses that will be used are only applicable for a fill ratio of 100%.

III. SPIN-UP INSTABILITIES

The instability mechanism of the Stewartson-Wedemeyer model is based upon a resonance between the fast precessional yaw frequency of the projectile and a natural frequency of oscillation (an eigenfrequency) of the spinning liquid. Much research has been conducted on waves in rotating liquids, commonly called inertial waves. The eigenfrequencies of these waves depend upon c/a, Re, the liquid fill ratio, and the velocity distribution within the liquid. If such a resonance occurs during spin-up, a generalized method does not exist for the estimation of the liquid moment. Murphy has devised an approximate method for the computation of a moment during spin-up, but this method is not applicable during early times.[11] During early times, viscous effects within the core region must be considered due to the presence of a critical layer. The flight data for the M687 instabilities are at sufficiently early times that the critical layer must be considered in the estimation of the moment. However, the eigenfrequencies during spin-up, with or without a critical layer, can be computed using the methods of Sedney and Gerber for the special case when the fill ratio is 100%.[12] A functional form describing the yaw growth rate of a spin-up instability is:

$$\text{Yaw Growth Rate} = \varepsilon = F\left(\tau,\ K_1,\ d\tau_{kn}/dt\right)$$

The ratio of the fast yaw frequency to the spin frequency is defined as τ. K_1 is the amplitude of yaw for the fast mode. The time rate of change of the liquid eigenfrequency is $d\tau_{kn}/dt$. It is clear that if $d\tau_{kn}/dt$ is large (this normally occurs early during spin-up), then the time of application of the resonant liquid moment is short and the yaw may not be affected. If, however,

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11. *C. H. Murphy, "Moment Induced by Liquid Payload During Spin-Up Without a Critical Layer," US Army Ballistic Research Laboratory, Aberdeen Ground, Maryland, BRL Technical Report in publication. (See also AIAA Paper 84-0229, January 1984.)*

12. *R. Sedney and N. Gerber, "Oscillations of a Liquid in a Rotating Cylinder: Part II. Spin-Up," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Technical Report ARBRL-TR-02489, May 1983. (AD A129094)*

$d\tau_{kn}/dt$ is small (as is the case late in the spin-up process), then the liquid moment acts over a longer period of time and the yaw may be drastically modified. Experience with the Stewartson-Wedemeyer model shows that the numerical values of the steady state eigenfrequencies are very sensitive to c/a. Hence, a large change in c/a could eliminate a spin-up resonance by completely shifting eigenfrequencies out of the range of τ. Perhaps a slight change in c/a could increase $d\tau_{kn}/dt$ and reduce the liquid induced moment to below the aerodynamic damping moment of the projectile.

IV. IMPORTANT CONCEPTS FROM STEADY STATE THEORIES

Several new steady state theories are available with various improvements to the Stewartson-Wedemeyer theory.[13,14] Figure 6 shows spin data (also unpublished data by Mark and Mermagen). Note that the spin frequency is approximately 94 Hz for all of the rounds in the 6-12 second time frame. A few comments must be made on the motion of liquid-filled shell. Spin-stabilized projectiles have two yaw modes: fast and slow. The slow mode is not affected by the presence of a liquid payload and is assumed to be stable, while the amplitude of the fast mode is affected by the liquid. Hence, typically only the fast mode is considered. The fast mode frequency for M687-type shell at transonic velocities is typically 8 Hz. (See Figures 3 and 4, for example.) Using the yawsonde determined yaw and spin frequencies, the ratio of the fast yaw frequency/spin frequency (defined as τ and now called the coning frequency) is approximately equal to 0.085. The methods developed by Murphy in Reference 13 will be used to obtain response plots (coning frequency versus yaw growth rate) and to identify parameters that will be used to explain the XM687 spin-up instability. Figure 7 is a typical steady state response plot for the XM687. (c/a = 4.901, fill ratio = f = 0.80, and Re = 1.85×10^6, and the selected coning frequency range is typical for the XM687.) The dimensionless yaw growth rate (ε) is computed for this frequency range. Yaw growth is predicted for $\tau = 0.03$. Since the expected τ for an XM687 is 0.085, then yaw growth should not occur. The local maximum in response plots (such as Figure 7) can be interpreted in terms of the eigenoscillations of the liquid. The linear theories[13,14] treat the liquid motion in terms of a modal solution with radial (n=1,2,3,..) and longitudinal (k=1,3,5,..) mode numbers. Only the azimuthal mode number 1 is considered since the other numbers do not produce a net moment on the projectile. The inviscid eigenvalues have a functional dependence upon only the aspect ratio (c/a), the fill ratio(f), and the mode numbers k and n. The corrected viscous

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13. *C. H. Murphy, "Angular Motion of a Spinning Projectile With a Viscous Liquid Payload," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report ARBRL-MR-03194, August 1982. (AD A118676) (See also Journal of Guidance, Control, and Dynamics, Vol. 6, July-August 1983, pp. 280-286.)*

14. *Nathan Gerber and Raymond Sedney, "Moment of a Liquid-Filled Spinning and Nutating Projectile: Solid Body Rotation," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Technical Report ARBRL-TR-02470. February 1983. (AD A125332).*

eigenvalues are complex and have a more complicated functional dependence. The real part corresponds to the frequency of the oscillation, while the imaginary part characterizes the damping of the mode. If the real part of the eigenvalue is negative, the wave motion is in a direction that is opposite to that of the spin. Yaw growth is not possible for this case. For $k \leq 9$, the c/ka values can be used to identify the possible eigenvalues

k	1	3	5	7	9
c/ka	4.901	1.634	0.980	0.700	0.545

The maximum probability for failure (see Figure 2) was for f = 0.80. For $k \leq 9$ and $0 \leq \tau_{kn} \leq 0.15$ the only possible inviscid eigenvalue is $\tau_{51} = 0.045$. For f = 1.00, only $\tau_{92} = 0.10$ is possible. (For f = 1.00, real part of $\tau_{51} = -0.0127$.) As in most vibration or resonance problems, the dominant responses are produced by the "lowest modes." Experience with gyroscope experiments has shown the n = 2 modes to be quite weak; hence, it is probable that a spin-up instability from the (k = 5, n = 1) mode caused the flight instability.

V. SPIN-UP EIGENVALUE HISTORY FOR THE (5,1) MODE

The methods of Reference 11 will be used to compute a spin-up eigenfrequency history for a 100% filled XM687-type projectile which will lead to the (5,1) steady state mode. Yawsonde data are not available for c/a = 4.901, but Figures 8 and 9 show flight data by D'Amico, Clay, and Mark for c/a = 4.972.[15] This projectile was launched under conditions similar to the DPG tests. Three XM687L rounds were tested, yet only one projectile (E1-9387) was unstable. This small sampling correlates well with the probability of failure predicted by Figure 2. Table 1 shows important physical characteristics. (Flight Reynolds numbers were approximately 1.85×10^6.) The canister height (2c) for the XM687L (L for long) is 2c = 53.41 cm. This is only 0.77 cm longer than the canister height of the XM687. The diameters of the two canister systems are identical (2a = 10.74 cm). The flight data for E1-9387 (an XM687L) will be used as a standard to explain the behavior of the unstable XM687's. A spin-up eigenfrequency history for E1-9387 is given by the solid line in Figure 10. For times beyond 30 seconds, the eigenvalue of the liquid is approaching a steady state value. Hence, application of steady state theories for the (5,1) mode can only be made beyond 30 seconds, and obviously flight instabilities were observed at much earlier times. For the data in Figures 8 and 9, $\tau = 0.08$. The time of a resonant matching between τ and a spin-up eigenfrequency occurs at 7 seconds. An expanded plot of the yawsonde data (Figure 9) indicates that the fast yaw mode began to grow at approximately

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15. *W. P. D'Amico, W. H. Clay, and A. Mark, "Yawsonde Data for M687-Type Projectiles with Application to Rapid Spin Decay and Stewartson-Type Spin-Up Instabilities," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report ARBRL-MR-03027, June 1980. (AD A089646)*

that same time. Hence, it is concluded that a (5,1) spin-up mode can produce the observed instabilities of the 100% filled XM687L and 100% filled XM687 projectiles. It is conjectured that this same instability mechanism also produced unstable flights for the 80% filled XM687 shell. It is probable that a (5,1) spin-up eigenfrequency for an 80% filled canister would be similar to Figure 10, such that at early flight times the steady state moment at $\tau = 0.03$ would occur as a spin-up moment at an earlier time for $\tau = 0.08$.

Using the methods in Reference 11, a calculation of the spin-up yaw moment was attempted. For the flight value of $\tau = 0.08$, it was not possible to compute the yaw moment at sufficiently early times due to the presence of the critical layer. Other cases of spin-up instabilities have been treated with some success, however, and comparisons with yawsonde data are available in Reference 16.

Table 1. Projectile/Canister Descriptions

Proj Type	Year	Boattail (cal)	c/a	a (cm)	Fill Ratio (%)
XM687	1972	1/2	4.900	5.37	80
M687	1974	1/4	4.390	5.37	80
XM687L	1978	1/2	4.973	5.37	100

VI. RATIONALE FOR THE SPACER USED WITHIN THE M687

The use of the spacer in the rear canister leaves 2c = 47.16 cm and reduces c/a to 4.391. The overall reduction in c/a from the XM687 to the M687 is 10.4%. Figure 12 (extracted from Reference 15) shows the effect of percent changes in c/a. Even a 5% reduction in c/a produces two results: the eigen-oscillation of the (5,1) spin-up mode is driven to negative values and $d\tau_{kn}/dt$ for $\tau = 0.08$ is substantially increased. The change in c/a produced by the spacer eliminated harmful responses from the (5,1) mode and did not cause other spin-up modes to produce destabilizing effects. It will not be speculated as to the original motivation behind the ad hoc spacer design. Stabilization was achieved and a rational explanation provided.

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16. *W. P. D'Amico, "Flight Data on Liquid-Filled Shell for Spin-Up Instabilities," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report ARBRL-MR-03334, February 1984. (See also AIAA Paper 83-2143, August 1983.) (AD A139136).*

VII. SUMMARY

The liquid-induced flight instability of the XM687 was reviewed. It was concluded that this instability was produced by a resonant matching between a liquid spin-up eigen-oscillation and the fast yaw frequency of the projectile. Yawsonde data support this conclusion. Computational techniques for spin-up eigenfrequencies also indicate that the spacer employed within the rear canister could be shortened to increase the payload mass by approximately 5%.

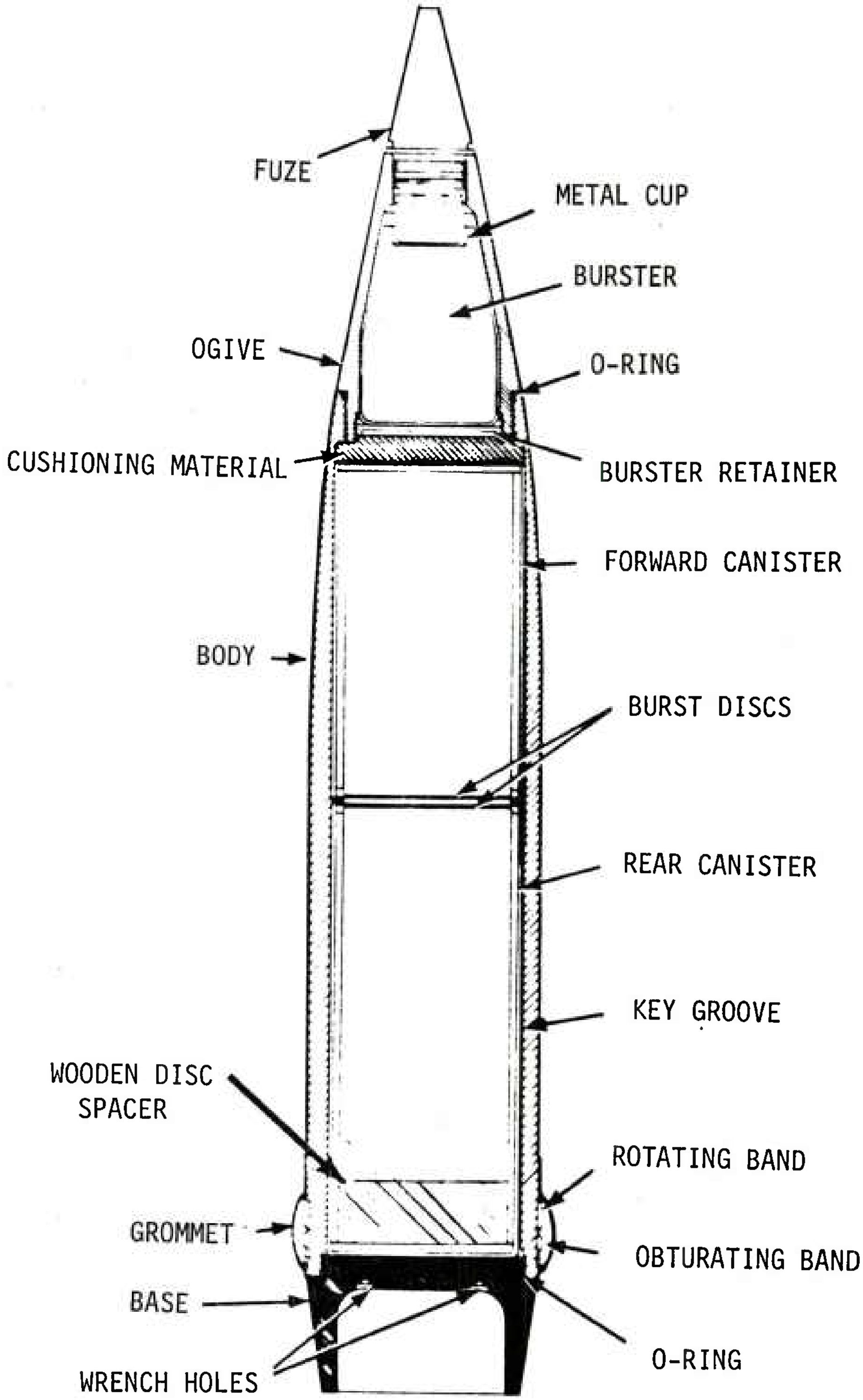

Figure 1. Cutaway View of the XM687 With a Half-Caliber Boattail.

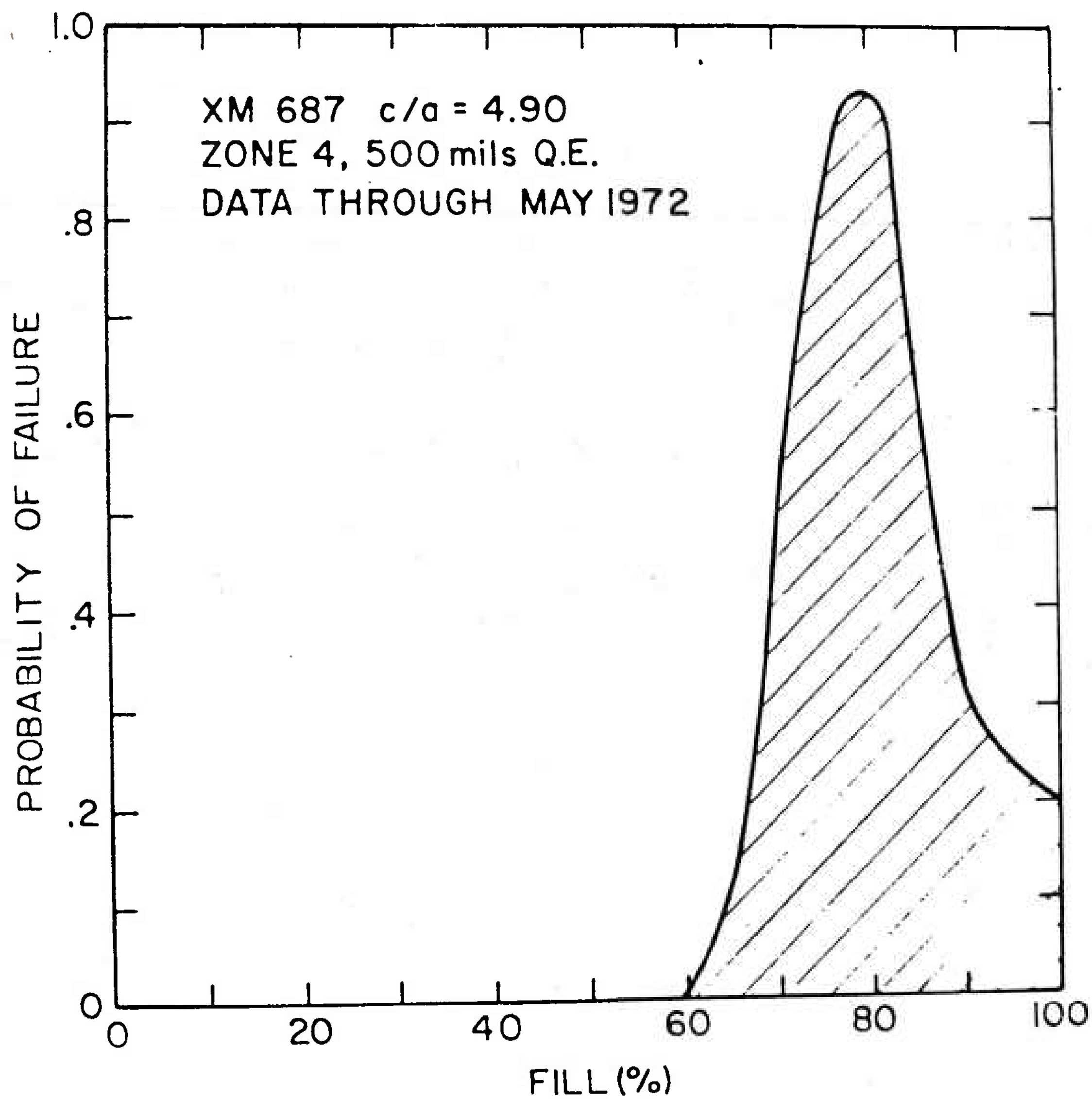

Figure 2. Probability of Failure (Reference 5).

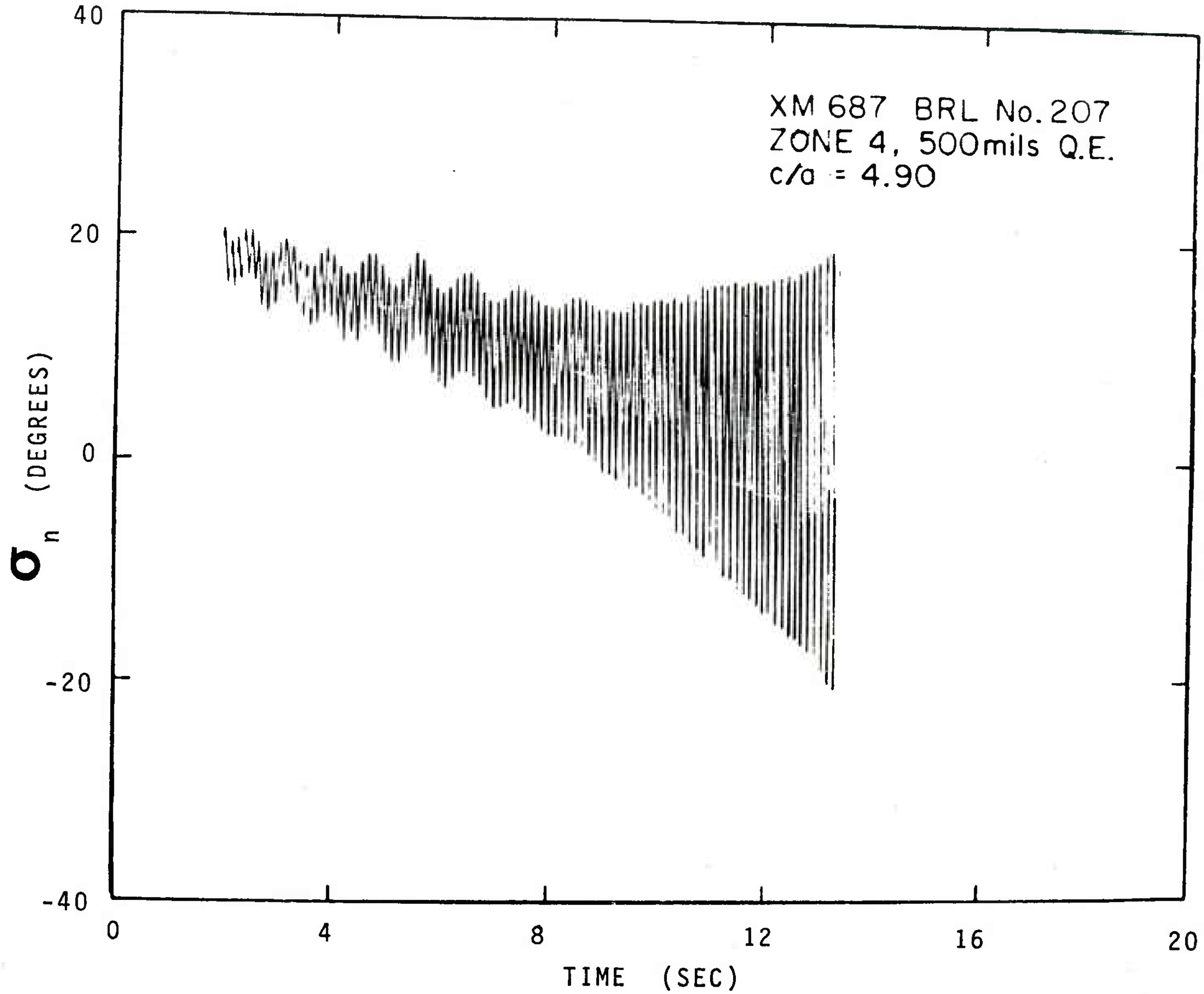

Figure 3. Yawsonde Data by Mark and Mermagen - BRL 207.

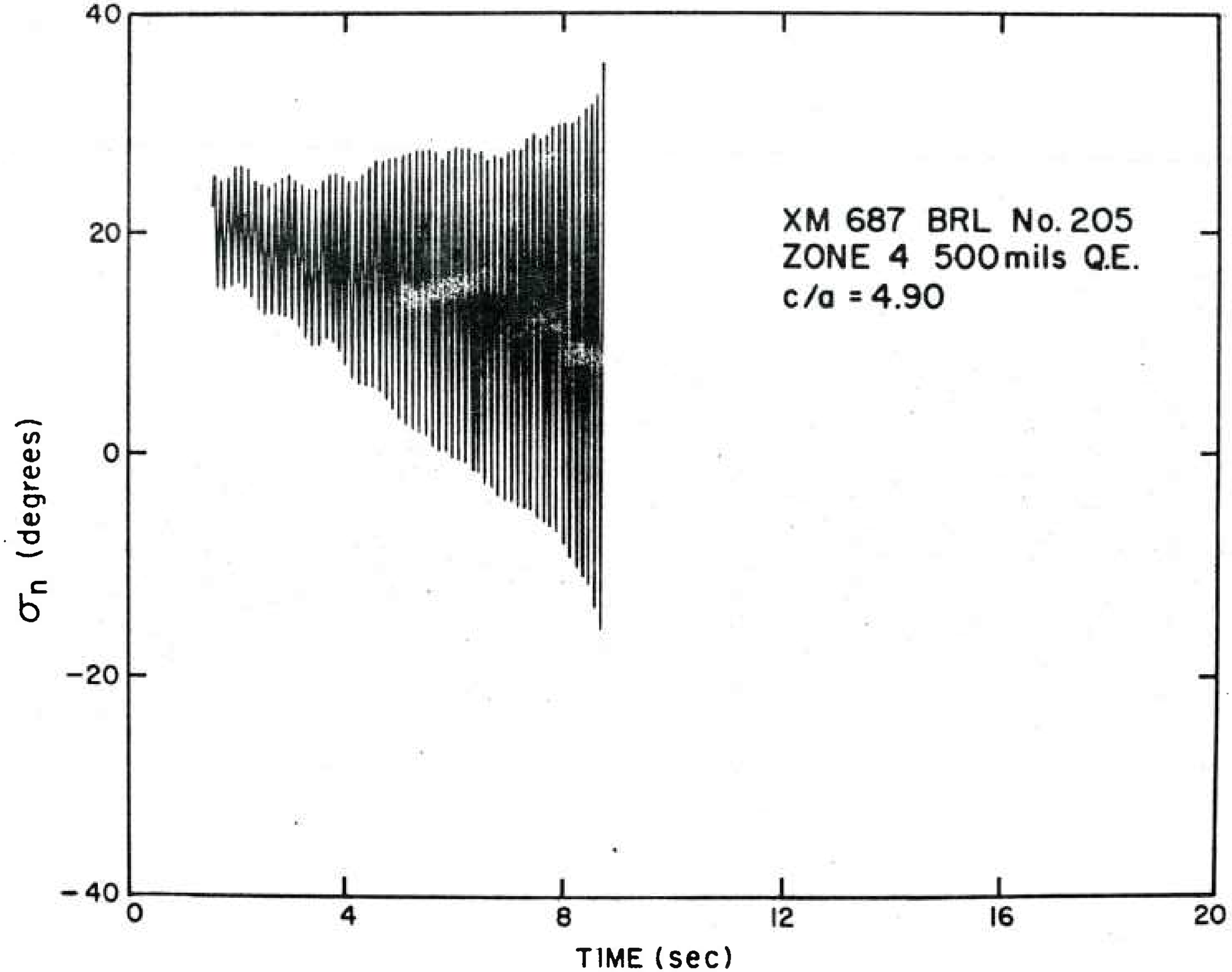

Figure 4. Yawsonde Data by Mark and Mermagen - BRL 205.

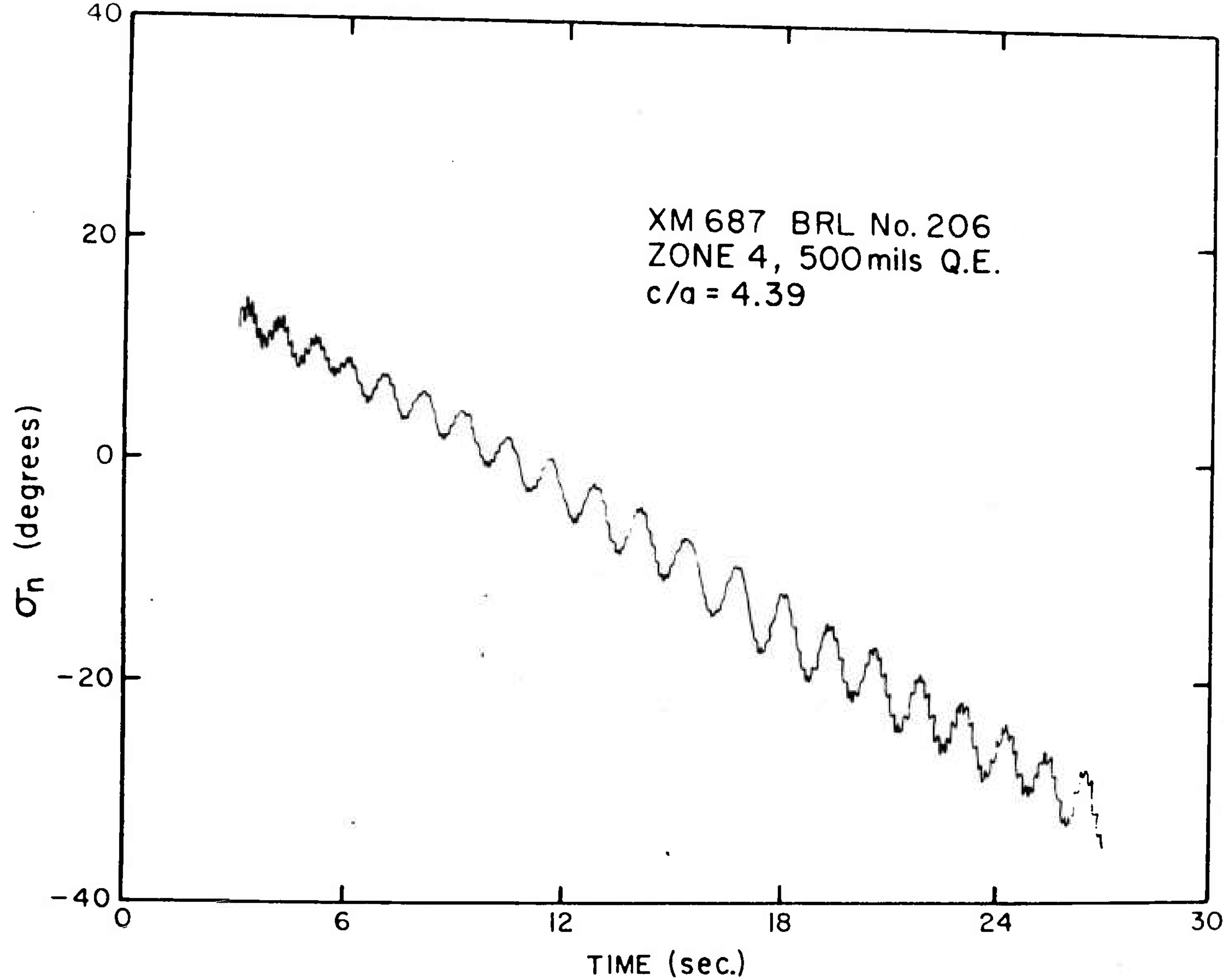

Figure 5. Yawsonde Data by Mark and Mermagen - BRL 206.

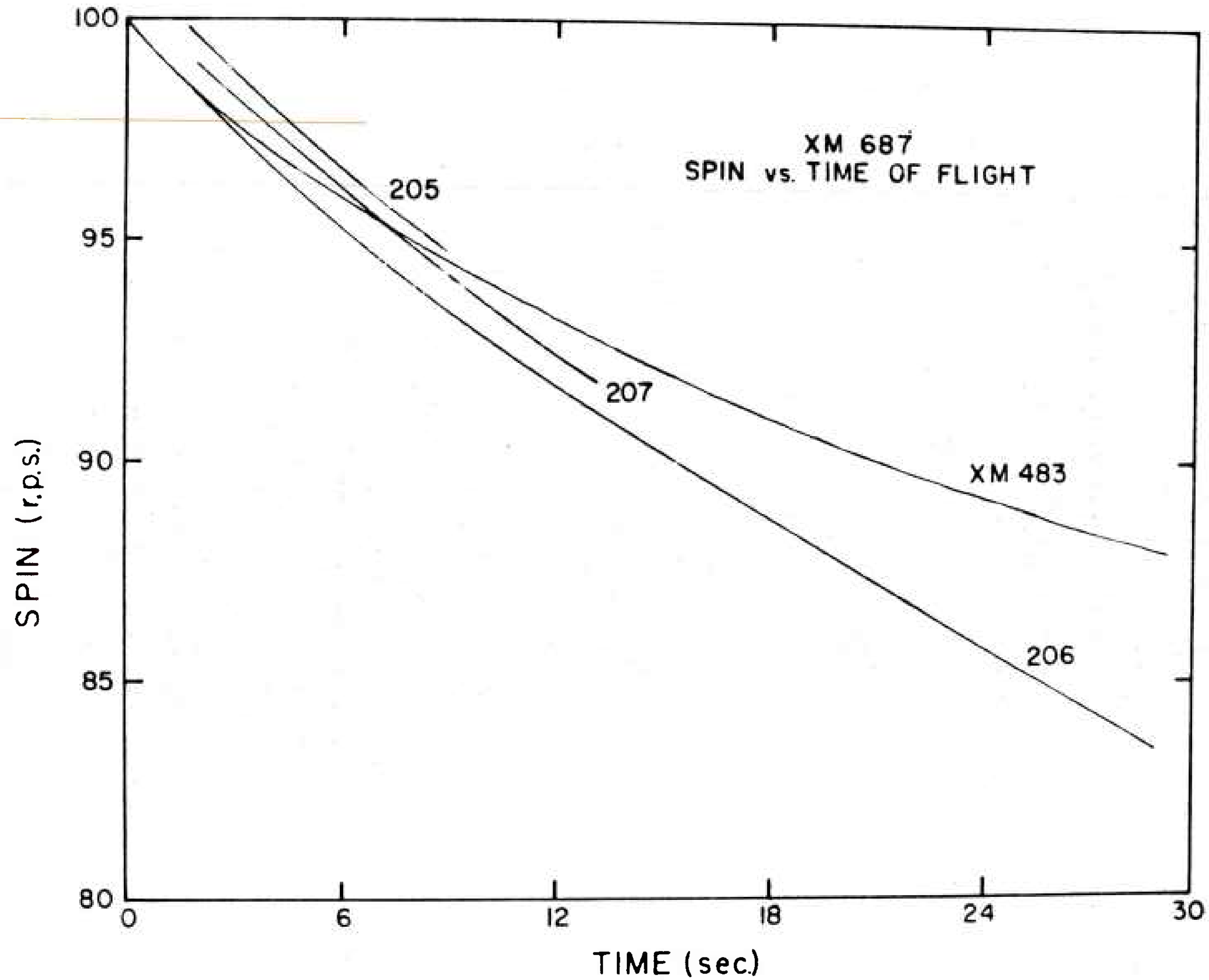

Figure 6. Spin Data by Mark and Mermagen.

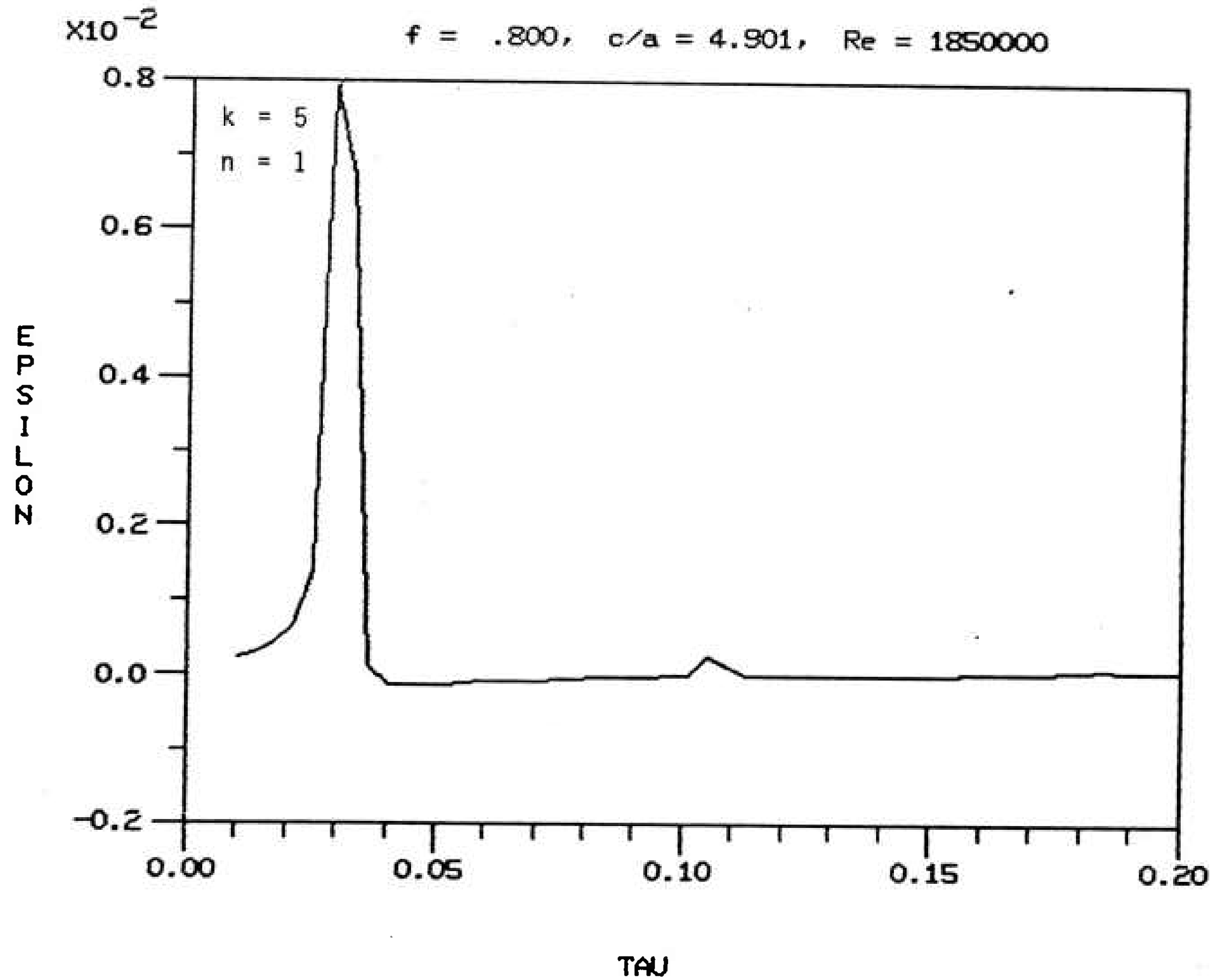

Figure 7. Response Curve for an XM687 Given Rigid Body Rotation of the Liquid Payload.

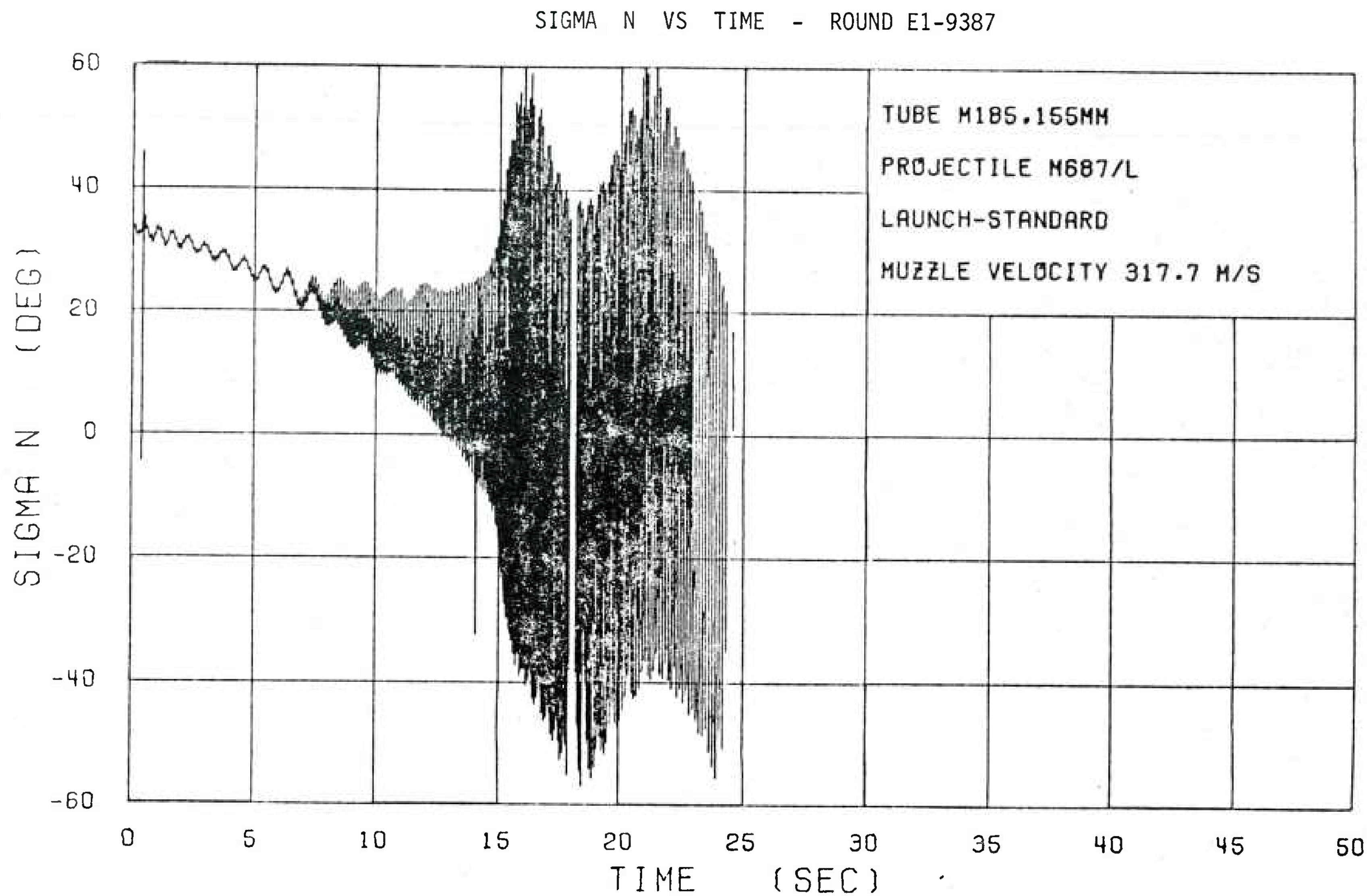

Figure 8. Yawsonde Data for E1-9387 (Reference 15).

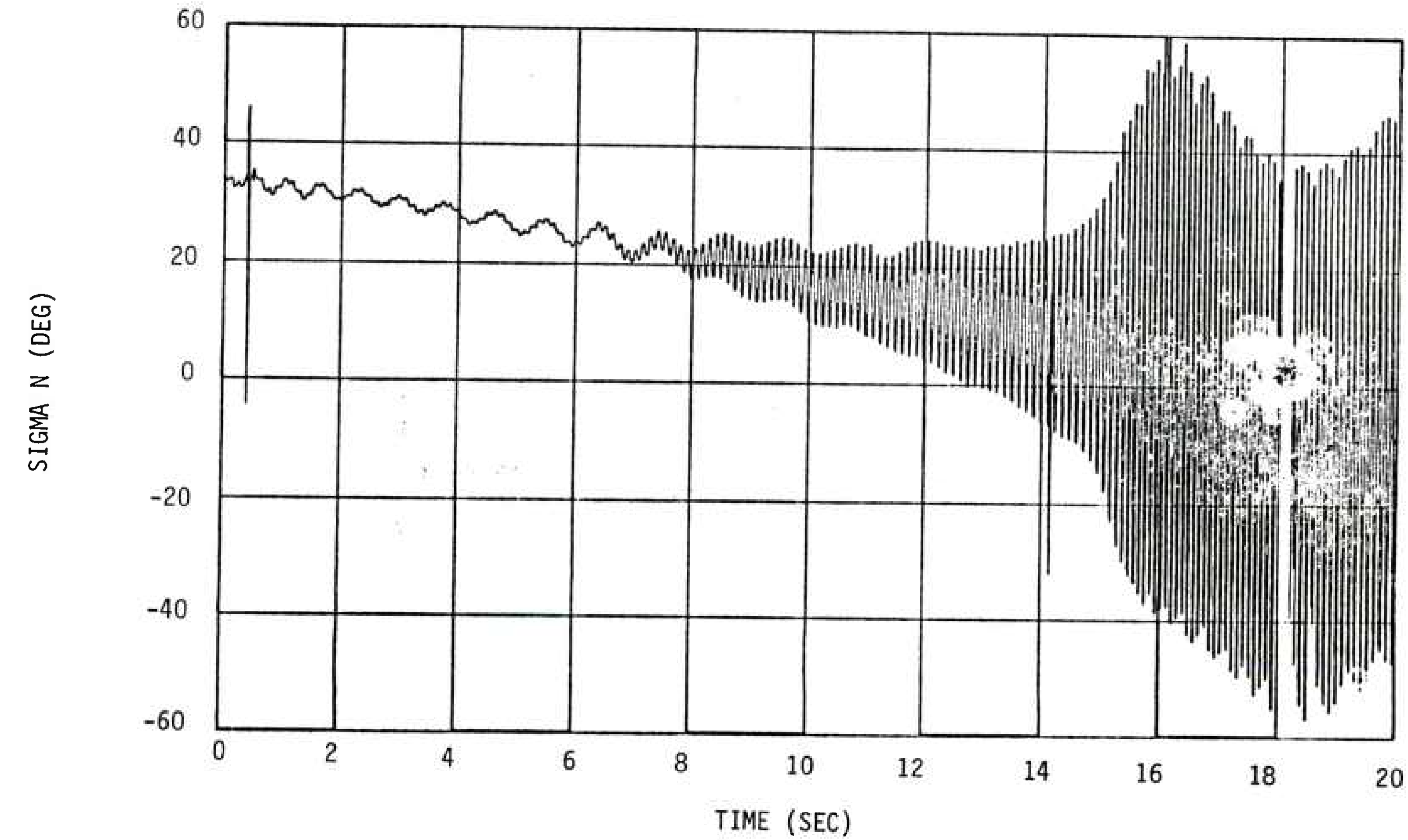

Figure 9. Expanded Yaw History for E1-9387.

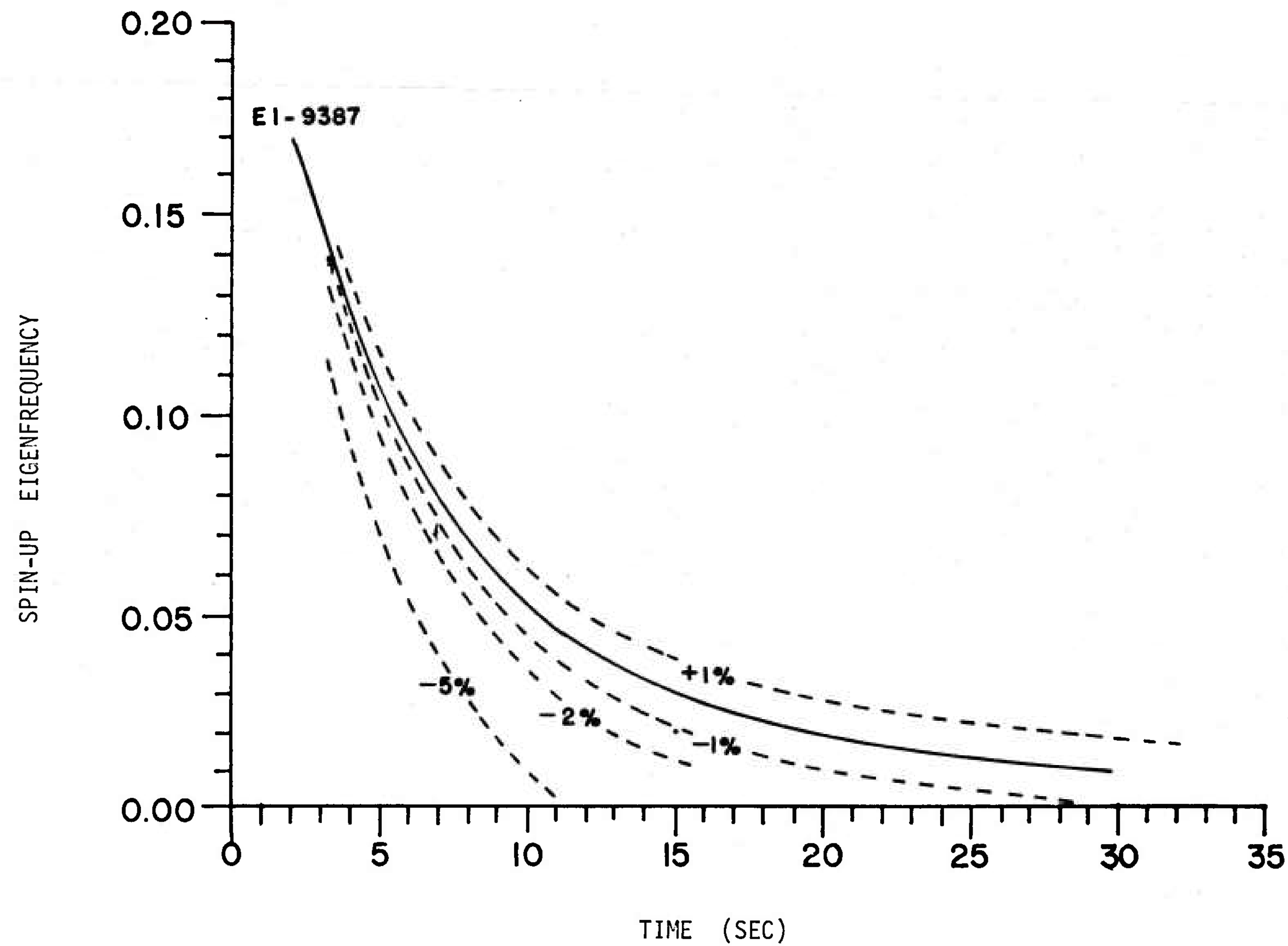

Figure 10. Spin-Up Eigenfrequency History for E1-9387.

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13. C. H. Murphy, "Angular Motion of a Spinning Projectile With a Viscous Liquid Payload," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report ARBRL-MR-03194, August 1982. (AD A118676) (See also Journal of Guidance, Control, and Dynamics, Vol. 6, July-August 1983, pp. 280-286.)

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